AN ANALYSIS OF SOIL CRUST STRENGTH IN RELATION TO POTENTIAL ABRASION BY SALTATING PARTICLES

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ABSTRACT

Wind erosion depends on the ease with which particles can be detached from the soil surface, but suitable tests to characterize this property are not available. Two possible methods to determine surface soil strength in the field were therefore compared on a range of artificially 'crusted' surfaces. These were made by spraying or tension wetting aggregates (10–2, 2–0·5 and <0·5 mm) from a structurally unstable sandy loam, followed by drying. Each test involved measuring the force exerted on a probe driven at a steady rate into the surface, using either a flat-tipped 0·6 mm diameter penetrometer or a flat-ended cylindrical punch with inner and outer diameters of 5 and 6 mm, respectively. Both probes showed that crusts could be produced reproducibly. Depending on the probe and aggregate size, penetration mainly occurred either as a result of aggregates being deflected out of the pathway of the probe or by genuine rupture of aggregates or of the crusted surface. The penetrometer, because it was comparable to the size of sand grains, gave results that can be used to characterize surface erodibility to saltating particles. The punch gave results that would be unsuitable for this purpose, as would other strength tests that are on too large a scale.

Penetrometer results were analyzed to calculate the energy required for penetration. It was thus possible to demonstrate that only the spray-wetted fine aggregates had a surface that could undergo large-scale rupture by saltating sand grains. For all other surfaces, saltating particles would be unable to supply sufficient energy to rupture aggregates or the crusted surface. Erosion could only occur by a slower process of abrasion in which smaller particles or aggregates are chipped away from the surface. However, it is shown that saltating particles could rupture the interaggregate bonding in the 2–0·5 mm aggregate surfaces, thus permitting creep. An alternative and potentially simpler way of characterizing surface erodibility by using a surface modulus of elasticity is also discussed. Our results demonstrate that the small diameter penetrometer is a promising technique for characterizing erodibility of aggregated and crusted surfaces. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Accurate predictions for the emission of dust particles from soils and sediments into the atmosphere during wind erosion are hampered by a lack of knowledge of the processes involved. The susceptibility of a particular soil to wind erosion depends on a variety of factors, including mineral composition, particle size distribution, degree of aggregation and/or crusting (the strength of bonding between particles, both physical and chemical), surface microrelief, local vegetation and geomorphology, agricultural practices, soil water, and wind flow characteristics.

Fine particles at the soil surface are frequently aggregated by being held to adjacent particles by bonding forces, including the effect of matric suction in any connecting annulus of water. The strength of the bonding between the particles affects the likelihood of individual particles being entrained by the local airflow, although small aggregates may be moved by sufficiently strong winds. Entrainment becomes increasingly more difficult when a surface is crusted. Even a weak crust has been shown to reduce the rate of erosion significantly (Gillette *et al.*, 1982), protecting the underlying less cohesive particles from aerodynamic forces. Chepil (1953, 1958) suggested that the erosion rate of crusted soils may vary by a factor of between 0·4 and 0·04 compared to that

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found for freshly cultivated fields, with an average value of about one-sixth. Zobeck (1991) found that some crusts may be very much more effective at reducing erosion. The range of comparative erosion rates calculated from his laboratory studies was between 0·2 and 0·0002. However, if interparticle bonds in aggregated or cemented surficial material can be ruptured, then fine particles may be detached for possible entrainment into the windflow and the rate of erosion will increase. This is well illustrated by the observations of Bagnold (1960), who noted clouds of dust produced after animals had broken up a surface that had previously resisted entrainment by aerodynamic forces alone. Similar breakage of interparticle bonds occurs after traffic on, or cultivation of, dry soils. High energy impacts of saltating particles can also break interparticle bonds. McTainsh (1985) reports that the incursion of saltating dune sands across dry lake surfaces causes dust entrainment. Loose coarse grains may also be left on the surface after the formation of a crust by wetting and drying of the sediment (Hagen *et al*., 1988; Potter, 1990). Saltation of these grains can also cause abrasion and attrition of the crusted surface.

Once particles are detached from any type of surface, they are available for entrainment into the saltation cloud (provided that the local windflow can sustain the movement), and contribute to further detachment and erosion. This erosion is affected by the quantity and energy of the abrading material and by the physical and chemical properties of the substrate (Zobeck, 1991). The composition of the surface is important, although a large proportion of fine particles does not necessarily imply a significant dust source. Sediments are not easily eroded if they contain more than 10 per cent clay, unless the surface has been broken up by agricultural practices, such as tilling. Because they are less cohesive, sands and sandy loams are more important dust sources (Pye, 1989), particularly when any surface crusting has been disturbed. The degree of cohesion between individual particles is a major factor in their erosivity (Smalley, 1970). Cohesion is reflected in the tensile strength of the surface. This property measures a characteristic that indicates susceptibility to erosion regardless of the history of formation of the surface. Strength measurements may therefore be made on artificially constructed surfaces and observations extrapolated to a variety of natural surfaces having similar strengths.

Standard tensile strength tests are usually conducted in the laboratory on natural or reconstituted samples. The modulus of rupture test (Richards, 1953) is conventionally performed on remoulded samples and is difficult to modify for undisturbed weak pieces of crust. Similarly, the aggregate stability test of Skidmore and Powers (1982), which measures the energy required to crush a sample between parallel plates, is not readily adapted to characterize weak crusts. Since weak crusts are extremely difficult to transport, it is desirable that crust measurements can be done in the field as well as in the laboratory, and that the method adopted is sensitive to both delicate and strong crusts. Penetration tests, particularly those that use cone penetrometers, have been widely used to measure the strength of the near-surface soil in the field (or in the laboratory), because measurements can be made quickly and easily (Campbell and O’Sullivan, 1991).

Any soil surface will have inhomogeneities due to differences in particle distribution and particle bonding. Where a strong surface contains a number of weaker patches, these patches may be eroded preferentially and undermine the surrounding strongly bonded crust or aggregate. Thus it is important to determine the distribution of surface strength values as well as mean values. For this reason, in determining surface strength in relation to abrasion by saltating particles, it seems likely that the strength test should be on a scale that is comparable to the size of the saltating particles. Any local failure is likely to be on this scale rather than at a macroscopic level.

This paper therefore compares two new methods of measuring surface strength properties that can be used both on delicate and strong crusts, and could be used in the field. Flat-ended penetrometers were chosen because they give a representative measurement over a known area. One device had a diameter comparable to that of saltating particles and the other was a circular punch with a much greater contact area, but which might be capable of obtaining some average readings more quickly. The smaller penetrometer was also used to determine a surface modulus of elasticity and to study its relationship to surface strength. Comparison of results from the two tests required surfaces with reproducible properties.

Because natural crusts and other surfaces are difficult to sample and transport successfully, artificially crusted surfaces were created in the laboratory. No attempt was made to simulate the environmental histories of natural soils, such as raindrop impact. Although the experimental surfaces were not direct analogues of specific

field conditions, their strength in relation to potential erosion is likely to be representative of a wide range of soil surfaces. The samples were either sprayed with water to produce delicate crusts, or tension-wetted to produce a stronger crusted layer comparable to the surface of a hardsetting soil (Mullins *et al*., 1990).

EXPERIMENTAL METHOD

Sandy loam topsoil with 490, 200, 60, 90 and 160 g/kg of particles 2000–200, 200–60, 60–20, 20–2 and <2 µm, respectively, was used for all samples. This soil (Plum Orchard), which is described in Young *et al*. (1991), is potentially hardsetting and slakes readily. Slaking is the process that occurs when dry aggregates are immersed in water and disintegrate into smaller fragments (Marshall *et al*., 1996; Mullins *et al*., 1990). Even without the influence of raindrop impact, this process causes structural disintegration in the upper horizon of many structurally unstable soils. On drying, a hard structureless layer forms, which is referred to as a hardsetting horizon. Such hardsetting soils are one of the major soil types in semi-arid tropical and subtropical areas (Mullins *et al*., 1990).

Sample preparation

Air-dry soil was sieved into three aggregate size ranges, <0·5 (fine), 0·5–2 (medium) and 2–10 mm (coarse). Samples of each aggregate size were placed in circular metal trays, 178 mm in diameter and 25·4 mm in depth. The trays had a basal layer of a dune sand (mean diameter 300 µm), which was covered with soil aggregates to a depth of 10 mm and then smoothed level with the rim of the tray. Each aggregate size was subjected to two different wetting regimes and two methods of measuring the strength of the soil surface. Duplicate trays were used for each combination of wetting regime and strength test.

The soil in each tray was wetted to encourage the subsequent formation of surface crusts as the soil dried. Half the trays were sprayed with approximately 100 cm^3 of deionized water from a household spray. This produced droplets that were fine enough not to disturb the surface. The other set of trays was tension-wetted by slowly feeding deionized water at a constant rate from an elevated reservoir via a plastic tube into the sand at the base of the trays. After about 1 h the water level was flush with the rim of the tray. The water feed tube was clamped and the tray left at ambient laboratory temperature overnight. These trays were then oven-dried at 40°C for 48 h. The trays that had been sprayed were also left to dry overnight and were then oven-dried at 40°C for 24 h.

Crust strength measurement

Each combination of aggregate size and wetting method was measured for surface strength using one of two ‘penetrometers’. These were mounted on a constant-rate drive, which operated at 0·67 mm min^{-1}. The trays were placed on a top pan balance interfaced to a datalogger and the applied load ±10 mg was recorded every few seconds. The larger penetrometer was a cylindrical punch, with a flat end, an outside diameter of 6 mm and an inner diameter of 5 mm. Nine penetrations were performed for each tray, each consisting of 99 readings taken at 4 s intervals. The maximum penetration depth was therefore 4·4 mm. The smaller penetrometer was made from a 0·6 mm diameter stainless steel lace pin with its tip filed flat. It had an unsupported length of 10 mm. Twenty-five penetrations were performed per tray, each consisting of 99 readings at 2 s intervals. The maximum penetration depth was therefore 2·2 mm. For both devices, replicate penetrations were made at roughly even spacings. However, care was taken not to bias the readings in favour of any particular type of encounter. For convenience, the large device will hereafter be referred to as the ‘punch’ and the other as the ‘penetrometer’.

Black and white photographs were taken of the trays before and after the penetration tests. During the tests a video camera was set up so that (i) the position of the penetrometer in relation to surface aggregates could be assessed, (ii) the start of the test (when the penetrometer was almost touching the surface) could be more accurately judged than by viewing the actual surface alone, and (iii) movement of the contact aggregate or those adjacent to the contact point could be observed. All tests were viewed on a monitor and about one-fifth were recorded on video tape.

The general position of the penetrometer in relation to the underlying aggregate or particle was observed for the first half of the trays examined. For the remaining (duplicate) samples this position was classified into three

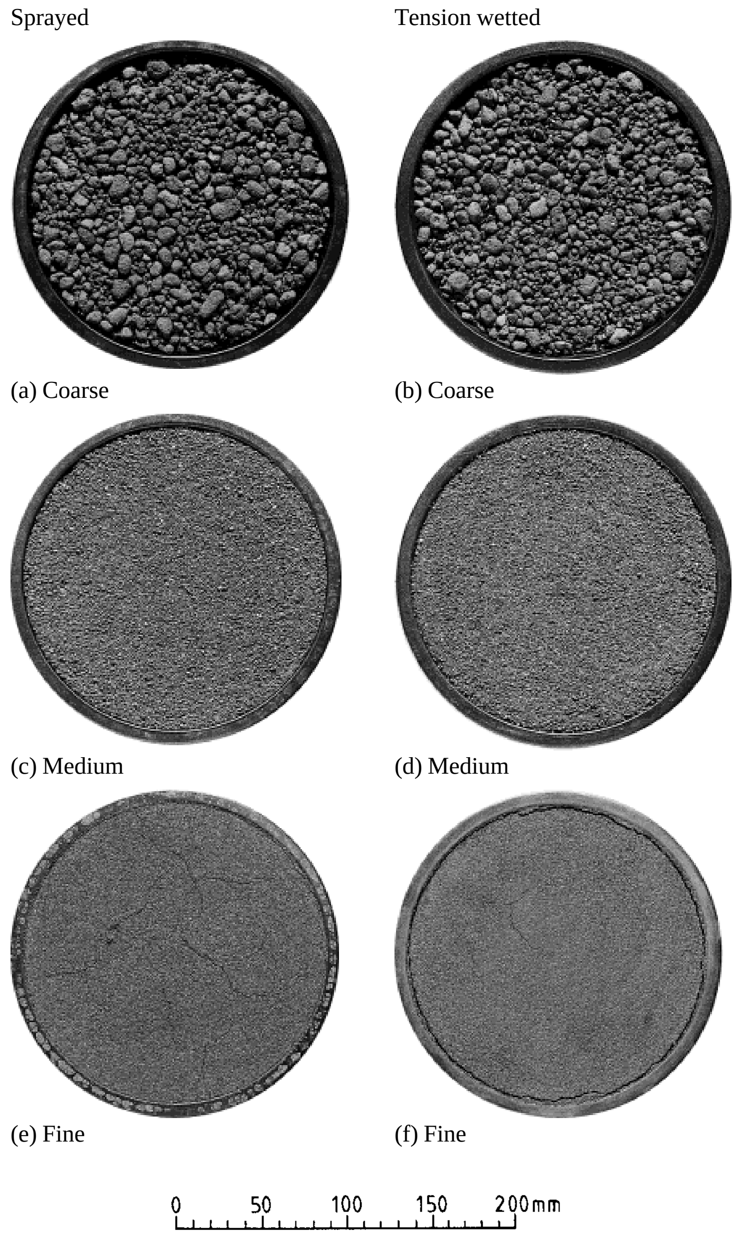


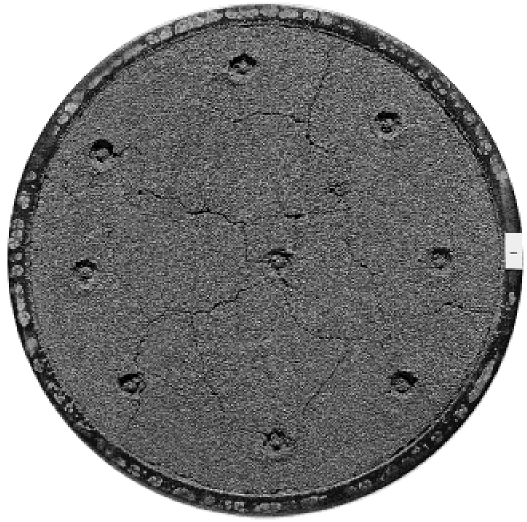
Figure 1. Plan view of soil trays prior to penetration tests

possible situations, (i) above the centre of the aggregate, (ii) off-centre or on the edge, or (iii) between aggregates.

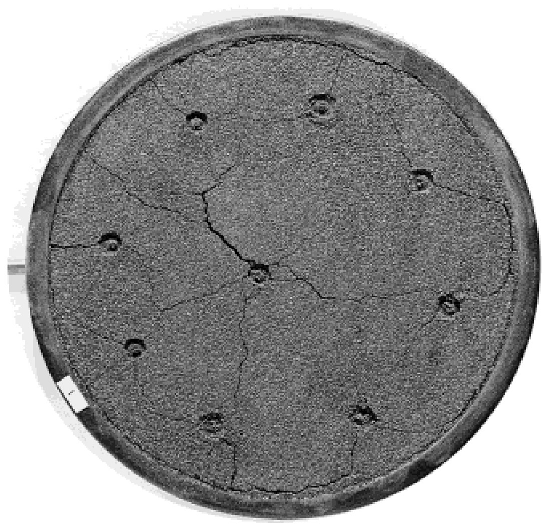
RESULTS AND OBSERVATIONS

Surface appearance

Figure 1 shows the surfaces of representative trays for each experimental condition prior to the penetration tests. With the 2–10 mm aggregates, the largest aggregates had long axes of up to 20 mm, which tended to lie parallel to the surface. When the material in the trays was levelled, the top surface of the larger aggregates was



(a) Sprayed, fine



(b) Tension wetted, fine

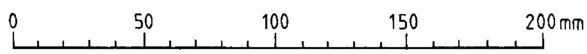


Figure 2. Plan view of fine aggregates after punch penetration

flush with the tray rim, with smaller aggregates in lower level pockets between them (Figures 1a, 1b). No visible differences were seen between the sprayed and tension-wetted surfaces. Crusting was not evident and the aggregates appeared to be separate from their neighbours. The surfaces of the sprayed and tension-wetted medium aggregates (Figures 1c, 1d) also appeared similar visually. Fine cracks formed on the fine, sprayed aggregates as the surface dried. The cracks were deeper and wider in the tension-wetted material (Figures 1e, 1f). Penetration did not significantly affect the surface away from the penetrometer or punch location, except for the fine material tested with the punch, where the penetration resulted in considerable further cracking for both wetting treatments (Figure 2). Further punch tests avoided these cracks.

Reproducibility of and differences between artificially crusted surfaces

There was great variation between individual tests performed on any one tray. Figure 3 shows examples of plots of applied load in relation to penetration depth for the penetrometer (Figures 3a, 3b), and the punch

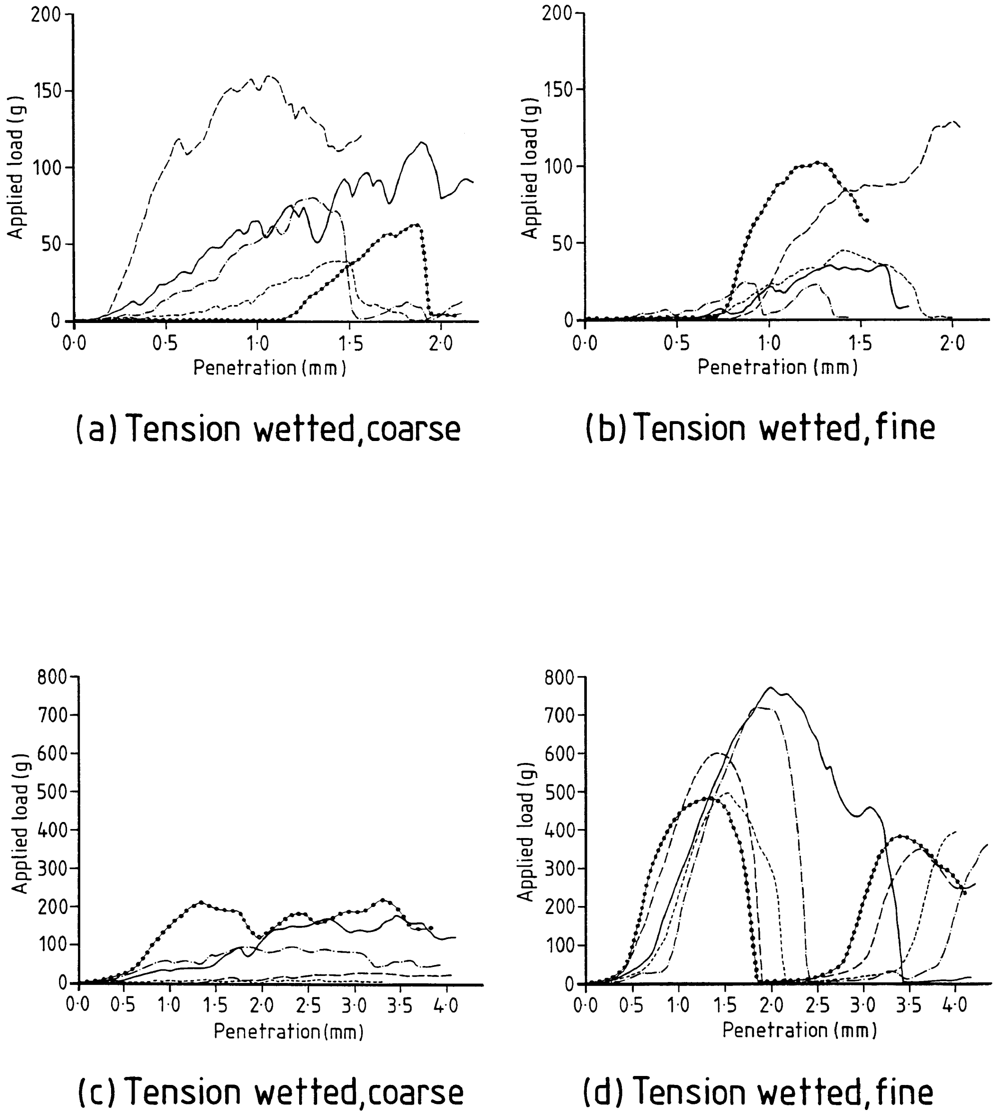


Figure 3. Examples of plots of applied load in relation to penetration depth: (a) and (b) for the penetrometer; (c) and (d) for the punch

Table I. The mean maximum penetration pressure (MMPP, $kN\,m^{-2}$) exerted by the punch and penetrometer, and coefficients of variation (CV, %) for penetrations in duplicate trays (a) and (b).

Aggregate size (mm)	Punch (n=9)								Penetrometer (n=25)							
	Sprayed				Tension wetted				Sprayed				Tension wetted			
	a		b		a		b		a		b		a		b	
	MMPP	CV	MMPP	CV	MMPP	CV	MMPP	CV	MMPP	CV	MMPP	CV	MMPP	CV	MMPP	CV
2—10 (coarse)	31·9 ±3·9	37	40·1 ±10·5	78	109·1 ±26·5	73	84·0 ±14·5	52	1484 ±301	101	1472 ±333	113	1924 ±394	102	1687 ±403	120
0·5–2·0 (medium)	5·7 ±0·9	46	7·4 ±0·7	29	15·9 ±1·6	31	12·4 ±2·2	54	5·2 ±2·0	188	5·1 ±1·5	147	17·4 ±4·3	123	14·5 ±5·0	173
<0·5 (fine)	10·4 ±2·4	70	7·8 ±1·1	43	594·2 ±60·8	31	339·5 ±28·8	25	32·6 ±7·2	110	28·2 ±5·2	92	1484 ±246	83	1637 ±207	63

(Figures 3c, 3d). Penetration resistance values had usually peaked before the full depth of penetration, so that the maximum value for each penetration can be taken as a strength value characteristic of the top 2 mm or 4 mm (for the punch) of the surface. Mean values of maximum force per unit area (or the mean maximum penetration pressure (MMPP)) for the replicate penetrations are given in Table I. The distributions of maximum values were markedly skewed, with very large standard deviations. Reproducibility of the MMPP values for the duplicate surfaces has therefore been tested using the Kolmogorov–Smirnoff test in conjunction with the Bonferroni test at a 5 per cent significance level (Campbell, 1989; Rasmussen, 1992). Between replicate sample trays the sets of penetrometer values did not differ significantly. This was also true for all comparisons between replicate punch tests, except for the fine, tension-wetted treatment. For both tests, for any given aggregate size, sprayed and tension-wetted samples had significantly different sets of strength values, apart from the penetrometer results on the coarse samples. For both sprayed and tension-wetted samples, different aggregate sizes had significantly different sets of strength values with the exceptions of the medium and fine sprayed samples tested with the punch, and the coarse and fine tension-wetted samples tested with the penetrometer.

Performance of the punch and penetrometer

For any given treatment, coefficients of variation for the MMPP values (Table I) were always greater for the penetrometer (63–188 per cent) than for the punch (25–78 per cent). This was expected and demonstrates that the smaller penetrometer is sensing much more of the small-scale heterogeneity which tends to be averaged out under the large contact area of the punch.

Using the penetrometer, the coarse aggregate always had larger MMPP values than the fine aggregate (49 times greater for the sprayed samples and 1·2 times greater for the tension-wetted samples). A similar trend is found for the punch with the sprayed coarse and fine aggregates (the MMPP is four times greater for the coarse aggregate). However, for the tension-wetted aggregates, the MMPP for the fine aggregates is five times greater than for the coarse aggregates. This demonstrates very clearly that the two tests are not always responding to the same surface strength properties. Both tests show that the tension-wetted treatments had greater MMPP values than the sprayed treatments for the coarse aggregates (2·7 times greater for the punch and 1·2 times greater for the penetrometer). Similarly, the medium aggregates show increases of 2·2 and 3·1 for the punch and penetrometer, respectively. There are much larger differences (51-fold in each case) between the sprayed and tension-wetted surfaces of the fine aggregates.

The MMPPs recorded do not show a consistent trend from coarse to medium to fine aggregates. This is because, for the medium aggregates, both the punch and penetrometer were able to push many of the underlying aggregates out of the way. Although tension-wetting increased the MMPP two or three-fold, the surface appeared to have little interaggregate cohesion. The aggregates could be moved aside by the probes with a comparatively small pressure. Movement of aggregates was sometimes seen in the fine, sprayed samples, and also occurred in some of the finer areas of the very diverse surfaces of the coarse aggregate samples. Thus, for both tests, the much smaller values of MMPP for sprayed, fine samples are partly attributable to deflection of aggregates out of the path of the probes in comparison to the tension-wetted surfaces, where slaking and hardsetting (Mullins *et al*., 1990) have produced a stronger, more cohesive surface layer in which considerable coalescence of the aggregates has occurred.

Frequency distributions

Maximum pressure. Maximum pressure distributions for the penetrometer were all markedly skewed towards the lower values, with occasionally a second mode at a higher value, when plotted on a linear scale. However, for ease of comparison, Figure 4 shows typical probability distributions of MMPP on a logarithmic scale. There were too few strength tests for the punch data to show any pattern in the frequency distributions.

Penetration energy per unit area. Distributions of energy per unit area values are plotted in Figure 5, with each individual value calculated as the sum of each penetration pressure up to the maximum value multiplied by the penetration depth interval. For the penetrometer, all of the distributions were again markedly skewed towards the lower values, so Figure 5 is shown as a log-linear plot. The maximum penetration energy per unit area for each condition ranges from 0·0081 kJ m^{-2} for the sprayed medium aggregate (Figure 5b), to 5·4 kJ m^{-2} for the sprayed and tension-wetted coarse aggregate (Figures 5a, 5d).

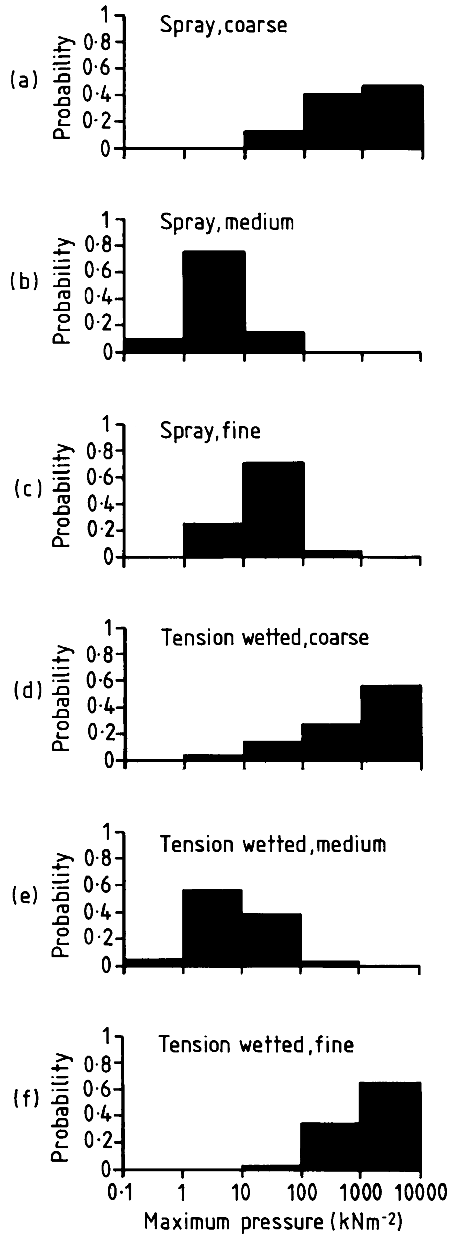


Figure 4. Probability distributions of MMPP obtained with the penetrometer

The frequency distributions for the punch were usually less skewed towards lower values than for the penetrometer, when plotted on a linear scale. They also tended to have more restricted distributions (see, for example, Figure 6). The total energy expended until rupture of the surface by the punch shows mean values of the same order of magnitude as for the penetrometer, except for the coarse aggregates (Table II). Maximum energy values are also shown in parentheses in Table II. Because the punch reading averages over the behaviour of a set of aggregates, both the coefficient of variation (CV) and maximum values determined by the punch are considerably less than for the penetrometer, except for the medium aggregates (where many of the aggregates could be pushed out of the way by the probe).

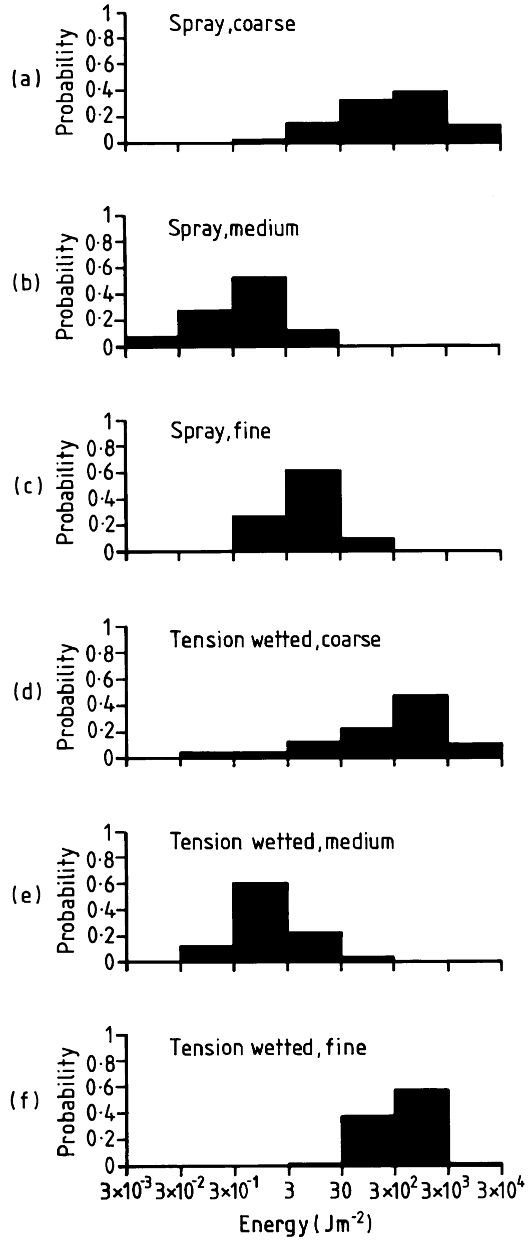


Figure 5. Probability distributions of the penetration energy for the penetrometer

Sampling position

The position of the probe relative to the underlying aggregates affected the magnitude of the force observed, particularly with the penetrometer. This was particularly clear for the penetrometer and coarse aggregates where, for the tension-wetted samples for example, typical MMPP values of 9–10 MN m^{-2} were recorded where the penetrometer encountered large aggregates head on (2 per cent of the total number of penetrations), values of 6–7 MN m^{-2} were found for encounters with the edges of aggregates (8 per cent) and values <1 MN m^{-2} were found for encounters with a collection of small aggregates, at the edges of small or medium aggregates, and where the penetrometer was deflected down the side of an aggregate (22 per cent).

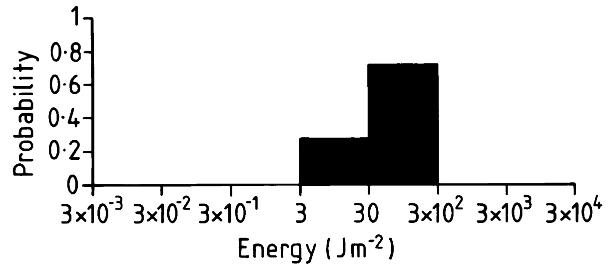


Figure 6. Probability distribution of the penetration energy for the sprayed, coarse aggregate using the punch

Table II. Mean values for the total energy expended until rupture ($J m^{-2}$) for the punch and the penetrometer, and coefficients of variation (CV,%). Maximum values are shown in parentheses.

Aggregate size (mm)	Punch (*n*=18)				Penetrometer (*n*=50)			
	Sprayed		Tension wetted		Sprayed		Tension wetted	
	Energy	CV	Energy	CV	Energy	CV	Energy	CV
2–10 (coarse)	46·2 ±7·2 (110·2)	66	136·7 ±30·6 (520·1)	95	1043·0 ±208·0 (5434·9)	137	1129·0 ±197·0 (5404·6)	121
0·5–2·0 (medium)	7·3 ±0·7 (13·6)	39	16·8 ±1·7 (37·0)	43	1·4 ±0·3 (8·1)	149	3·6 ±0·9 (31·8)	182
<0·5 (fine)	13·4 ±1·8 (35·3)	57	313·0 ±36·0 (716·7)	49	11·1 ±1·7 (54·1)	105	795·0 ±116·7 (3020·5)	104

DISCUSSION

Our results show that it was possible to manufacture reproducible artificial crusted or hardset surfaces with a wide range of strengths. We also found that, for the medium aggregates, both strength tests could detect significant differences in surface strength between sprayed and tension-wetted aggregates when there was no visual difference in surface appearance (Table I). The punch was also able to make this distinction for coarse aggregates. As expected, the tension-wetted fine aggregate samples gave the strongest surfaces. This was due to the greater proportion of these aggregates that slaked during wetting and then coalesced together with the finer material during drying to produce a strong, coherent surface. This type of behaviour, including the effect of aggregate size on slaking and hardsetting, has been described in detail by Bresson and Moran (1995), together with photographs of thin sections that illustrate the amount of interaggregate coalescence and bonding involved. Even with the coarse aggregates, which must have undergone comparatively little coalescence after wetting, both tests showed that the tension wetting resulted in a greater surface strength than spray wetting, although the difference was not significant for the penetrometer results because of their greater variability.

Suitability of the tests for estimating erodibility

The punch did not register the coarse aggregates as having a strong surface because aggregates were weakly attached to one another and they could be repositioned if the probe encountered more than one aggregate group. In contrast, the penetrometer registered the coarse aggregate samples to be over nine times stronger than indicated by the punch results. This was because the penetrometer tip was small compared to the size of the aggregates, and they did not usually move out of its path. In contrast, both the punch and penetrometer gave similar results for the medium-sized aggregates (Table I) which could move out of the path of both instruments. The contrasting way in which these two probes sense surfaces is very important because it demonstrates the importance of testing surface strength properties at the scale of interest. Saltating particles would encounter the surface in a manner that is much more similar to that of the penetrometer than the punch. They would not readily

erode the large aggregates, even if the aggregates were completely unattached to one another. Thus these results demonstrate clearly that strength tests that are not on a scale comparable to the size of saltating particles are unlikely to be of use in comparing the erodibility of different surfaces. However, this does not necessarily mean that the penetrometer results can be used to represent the erodibility of the surface. It is necessary to consider the possible mechanisms of erosion to address this question. There are two possible approaches to this: either to compare the energy delivered by individual saltating particles or to consider the force that each particle may be able to apply to the surface. We have tried both approaches.

Energy delivered by saltating particles

Zobeck (1991) and Rice *et al*. (1996a) have shown that the kinetic energy of impacting particles affects the erosion of crusted surfaces. Within any saltation cloud there will be a distribution of particle sizes and speeds (Anderson and Haff, 1988). A typical sand grain in the saltation cloud, with a diameter of 300 μm and a velocity of 1 m s^{-1} (Anderson and Hallet, 1986), would have kinetic energy of about 0·3 J m^{-2}. If a grain with diameter of 600 μm moving at 2 m s^{-1} is taken as the maximum size and speed of a well sorted dune sand transported under steady-state conditions in an average strength wind, then the approximate maximum value will be 2·12 J m^{-2}. Although not all of this energy will be dissipated on impact and only a proportion of it will be used to break bonds, these values provide an indication of the maximum energy (generated by moderate windflows) that can be dissipated during impact. This can be compared with the values of energy required to penetrate the surface shown in Figure 5. The latter values represent the total energy required to penetrate the surface to the depth at which the strength peaked (corresponding either to particle displacement or to a genuine rupture of the surface that could release more erodible material). For both types of coarse aggregated surface there were no penetration energies <3 J m^{-2} (unless the probe slipped down between two completely separate aggregates). As expected, this indicates that the saltating particles have insufficient energy to affect the surface by either releasing or breaking aggregates, although they may be able to abrade small pieces of material from the top of the aggregates.

The medium (0·5–2 mm) aggregates are in a size range of particles that can move as creep when hit by saltating sand grains. We have shown that the values in Figure 5 mainly correspond to the action of displacing aggregates from the path of the penetrometer. Since this process necessarily involves rupture of any interaggregate bonds, these values therefore indicate the energy required to disturb the surface. It is interesting to note that 35 and 78 per cent of penetrations in the spray-wetted, and 13 and 60 per cent of the penetrations in the tension-wetted samples required energies of <0·3 and <2·12 J m^{-2}, respectively. Thus, the spray-wetted surface is liable to be more vulnerable to creep than the tension-wetted surface, demonstrating the importance of even comparatively weak interaggregate bonding for this size of aggregates.

None of the penetrations in the tension-wetted fine aggregates had energies <2·12 J m^{-2} and all energies (except for one measurement) were more than two orders of magnitude greater than 0·3 J m^{-2}. In this case, and for both coarse aggregate treatments, the surface can only erode by abrasive wear that removes small portions of individual aggregates or particles and can ultimately undermine more resistant particles and break the bonds between them and the surrounding soil. However, the fine spray-wetted aggregates did have 21 per cent of rupture energies <2·12 and 0 per cent <0·3 J m^{-2}, indicating that detachment of material, probably including fine aggregates, was possible. In all other cases, ignoring penetration values corresponding to aggregate displacement without rupture, the energies required to rupture the surface were all comparable to or greater than the energy that could be supplied by individual sand grains.

Force applied by saltating particles

An impacting grain of mass m and with a component of velocity v which decelerates uniformly over a small distance δx during impact will have a deceleration $a = v^2/(2.\delta x)$. If the surface has some modulus of deformation $M_e = F/\delta x$, where F is the force required to produce a surface deformation δx, then:

$$F = v(mM_e/2)^{1/2} \tag{1}$$

M_e represents the rigidity or stiffness of the surface. M_e will depend on the area of contact and can be estimated

Table III. The percentage of penetrations where an impacting particle could have caused surface rupture. Values have been calculated for a 300 μm diameter particle travelling at several velocities.

	Sprayed					Tension wetted				
Aggregate size	1*	2	3	4	5	1	2	3	4	5
Coarse	0	0	0	0	0	0	0	0	0	3
Medium	0	8	25	33	50	0	0	27	50	50
Fine	0	3	5	14	19	0	0	0	0	0

* Particle velocity (in $m\,s^{-1}$).

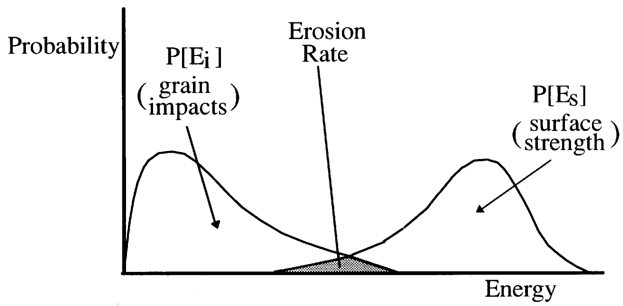


Figure 7. Schematic representation of probability distributions of the energy delivered to a soil surface by grains in a saltation cloud, $P[E_i]$, and the local energy required to break surface crusting, $P[E_s]$.

at the same time as the maximum penetration force from each penetrometer trace (described below). Equation 1 shows that the impact force transferred to an elastic surface by a rigid particle is proportional to v, $m^{1/2}$ and $M_e^{1/2}$. This equation gives the maximum force available for indentation and implies that a more rigid surface will experience a greater force. Thus it is not evident that a strong but stiff surface is necessarily less vulnerable to abrasion than a surface that is weak and soft.

It is to be expected that, like the surface strength, the surface deformational properties will also exhibit a large spatial heterogeneity so that it is necessary to consider the strength and modulus of deformation together at each location and to sample many different positions over the surface. We have determined approximate values for this modulus for each penetration by measuring the slope of the penetration plot between the first non-zero force registered (ignoring initial small peaks likely to be due to slight movement of the penetrometer over the surface) and the point of ‘failure’ which was estimated as the point where the penetration force decreased by at least 25 per cent.

Equation 1 suggests that local surface failure (where $F > F_{max}$) can only occur if:

$$\frac{v(mM_e/2)^{1/2}}{F_{max}} \geq k \tag{2}$$

where F_{max} is the maximum penetration force measured just before a decrease of at least 25 per cent, and k is a constant of order 1. Henceforth, suppose that k is equal to 1. Using typical values of $1\,m\,s^{-1}$ for v and $5{\cdot}86\times10^{-5}$ g for m (Willetts and Rice, 1986), the percentage of penetrations where this equation indicates that an impacting particle could have resulted in surface rupture is always zero (Table III, columns 2 and 7). However, Table III also shows the percentage of penetrations capable of surface rupture when higher velocities of 2 to $5\,m\,s^{-1}$ (values possible for 300 μm grains) are used in the equation. These results demonstrate the potental erodibility of both medium aggregates and the fine, sprayed aggregate at increased windspeeds. Conceptually, the heterogeneity of surficial material to erosion and the distribution of impact energies delivered by the saltating grains can be represented by the schematic diagram shown in Figure 7. The overlap of the two distributions indicates the rate of erosion. For a particular surface and given wind strength, the extent of the overlap is particularly sensitive to the shape of the adjacent tails of the distributions.

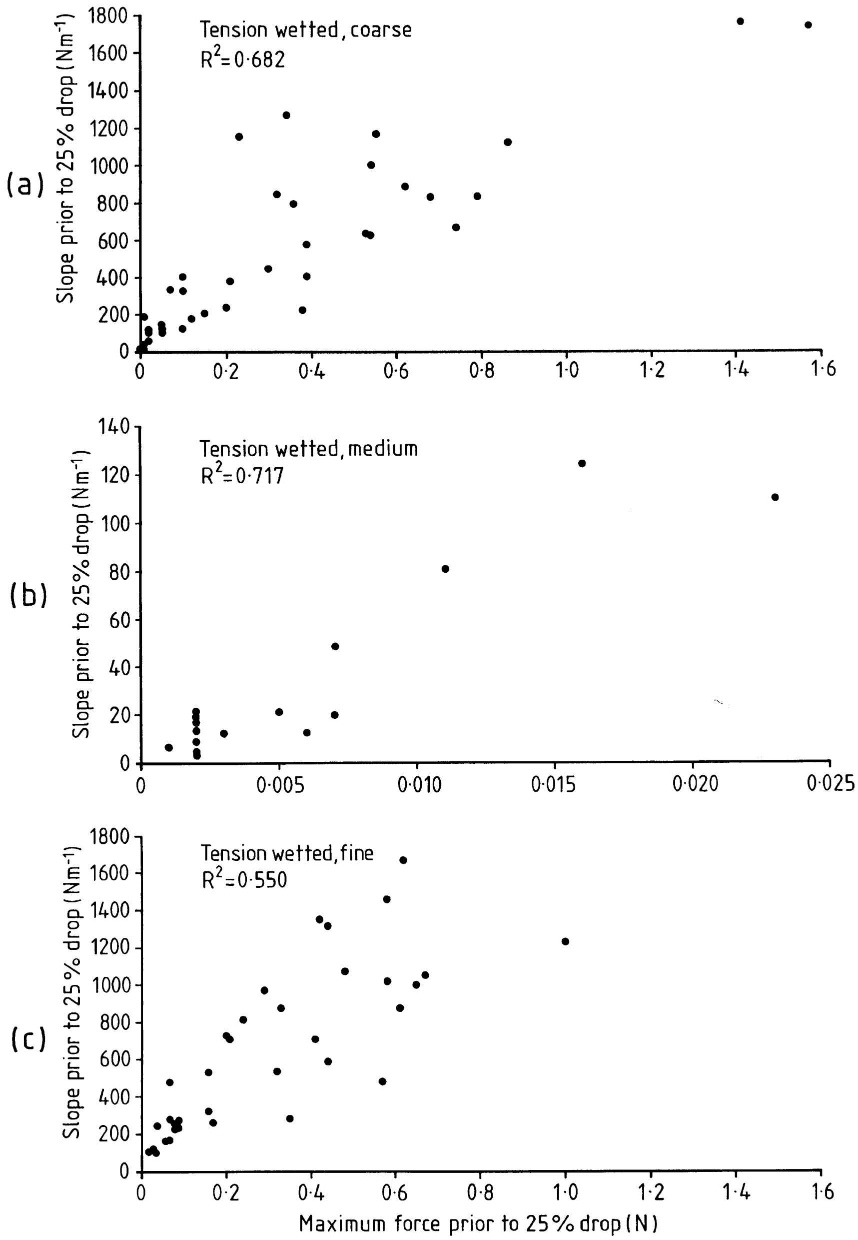


Figure 8. Examples of plots of the modulus of deformation (M_e) versus the maximum force (F_{max}) prior to a 25 per cent drop for the penetrometer

Table IV. Ratio of modulus of deformation to force (*b*) obtained from linear regression through the origin for the penetrometer results. r^2 is the coefficient of determination and *n* is the number of measurements.

	Sprayed				Tension wetted			
Aggregate size	*a*	*b* (m^{-1})	r^2	*n*	*a*	*b* (m^{-1})	r^2	*n*
Coarse	0	1182	0·388*	38	0	1316	0·682*	37
Medium	0	5326	0·689*	12	0	5106	0·717*	22
Fine	0	3153	0·473*	37	0	1849	0·550*	35

* Significance level of <0·001.

In mathematical terms the energy and force approaches differ only slightly in that the energy is calculated by integrating the area under the penetration curve whereas the surface modulus is only an approximate value. Thus it is not surprising that both approaches lead to the same conclusion. However, the force approach serves to indicate how two different surface properties, the strength of interparticle (or interaggregate) bonding and the surface elasticity, are both involved in determining erodibility. Furthermore, if these two properties are related, and a simple method can be devised to determine this relationship, it would be possible to characterize surface properties simply from a set of measurements of surface strength, which could be determined more easily and in much less time than measuring both properties.

Values of M_e were plotted versus F_{max} to determine whether there was a relationship between local values of surface strength and surface modulus. Examples of such plots are given in Figure 8. In general, for each type of surface, F_{max} increased with surface modulus. Significant linear regressions of M_e on F_{max} (Table IV) also showed that, for any given surface, M_e could be estimated from F_{max}, although a direct measurement would be more reliable. However, it is not yet clear if the coefficients required to describe this relationship could be determined in any other, simpler fashion.

Other considerations

One important point to bear in mind when considering soil strength measured by a vertical penetrometer is that impact forces are unlikely to be delivered at 90° to the surface. Mullier *et al*. (1991) observed that impacts with low angles of incidence caused a greater degree of damage than impacts with larger angles. Their experiments were with agglomerates hitting an inclined, roughened surface, and not for a granular bed being hit by a projectile. The latter situation, albeit with a cohesionless bed of sand-sized particles, was examined by Rice *et al*. (1996b). They found that the number of ejected grains per collision increased with increasing impact angle up to approximately 15°. Above this angle the number of ejections appeared to decrease, but the number of data points here was small. These results conflict with the generally accepted view that erosion due to brittle fracture is more rapid when impacts are at 90° to the surface (Hutchings, 1987). However, McEwan *et al*. (1992) suggested, from an analysis of collisions of saltating grains with a cohesionless flat surface, that a vertical, compressive force leads to rearrangement of grains, but a horizontal, shearing force is more likely to cause ejection. Saltating grains approaching at oblique angles may therefore cause more damage to surface layers than normal impacts. If this is true, then the comparison between the energy required to penetrate the surface with the penetrometer and the energy delivered by saltating grains underestimates the ability of the latter to rupture the surface.

The importance of collision energy for the release of dust particles into the air has been discussed by Gomes *et al*. (1990). They found two airborne particle size ranges from the Sahara Desert between 0·1 and 20 µm and between 20 and 200 µm, and suggested that the submicrometre particles are derived by a sandblasting process which disintegrates and/or comminutes soil particles. They speculated that 'collision momentum is sufficient to break the interparticle bond strengths and remove clay coatings from the surfaces of large particles'. The theoretical studies of Haff and Anderson (1993) certainly indicated that most saltating grains possess enough energy to cause local fracturing or spalling of surface grains and the impact grain itself, thus effecting surface break-up and the production of dust particles. The present study supports the idea that one saltating grain can deliver enough energy to sediment surfaces to disrupt interparticle bonding in weak to medium strength crusts or aggregates.

CONCLUSIONS

This study has demonstrated that:

(1) crusted soil surfaces can be reproducibly produced in terms of surface strength;
(2) the kinetic energy delivered to the surface by individual saltating grains is sufficient to cause penetration of weakly cohesive soils;
(3) surface erodibility may be characterized by using a modulus of elasticity;
(4) the rate of deflation for eroding soils will depend on the degree of overlap between distributions of the forces applied to the surface by saltating grains and the forces required to rupture local areas of crust or aggregates.

We consider that these laboratory tests could be extended to the development, for the field, of a rapid surface strength measurement using several penetrometers simultaneously over a given area. Measurement of a physical property related to the process of erosion is more likely to lead to a greater understanding of surface rupture and entrainment than useful, but largely empirical, measurements with a portable wind tunnel.

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